

## INTERNATIONAL SPACE STATION NICKEL-HYDROGEN BATTERY ON-ORBIT PERFORMANCE

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### ABSTRACT

International Space Station (ISS) Electric Power System (EPS) utilizes Nickel-Hydrogen (Ni-H<sub>2</sub>) batteries as part of its power system to store electrical energy. The batteries are charged during insolation and discharged during eclipse. The batteries are designed to operate at a 35% depth of discharge (DOD) maximum during normal operation.

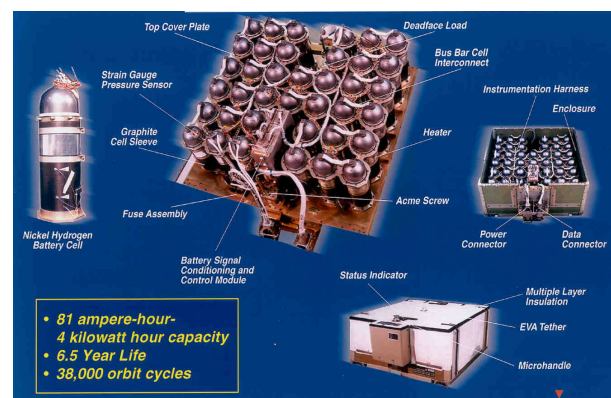
Thirty-eight individual pressure vessel (IPV) Ni-H<sub>2</sub> battery cells are series-connected and packaged in an Orbital Replacement Unit (ORU). Two ORUs are series-connected utilizing a total of 76 cells, to form one battery. The ISS is the first application for low earth orbit (LEO) cycling of this quantity of series-connected cells.

The P6 (Port) Integrated Equipment Assembly (IEA) containing the initial ISS high-power components was successfully launched on November 30, 2000. The IEA contains 12 Battery Subassembly ORUs (6 batteries) that provide station power during eclipse periods. This paper will discuss the battery performance data after eighteen months of cycling.

### INTRODUCTION

At Assembly Complete (AC), the ISS Electric Power System (EPS) will be powered by 24 batteries during eclipse and extended operation periods. The batteries are evenly divided between four Integrated Equipment Assemblies (IEA), as part of the four photovoltaic modules (PVM). The fourth and final PVM will complete the EPS and is currently scheduled for launch in January, 2004. The battery

ORU (see Fig. 1) is designed to operate for 6.5 years, with a mean-time-between-failure (MTBF) of 5 years, when run in the reference design 35% Depth of Discharge (DOD) low earth orbit (LEO) regime. Typical expected discharge currents can range from <25 Amps in a low-demand orbit to as high as ~75 Amps to meet short peaking load requirements at a battery operating voltage range of 76 to 123 Vdc. The ORUs are individually fused to protect the ISS EPS from fault propagation that could result from a cell-to-EPS ground event. Primary charge control is accomplished by a pressure temperature algorithm, which incorporates acceptance test data in order to initialize basic reference parameters.



**FIGURE 1. ISS BATTERY SUBASSEMBLY ORU**

The ISS power system is the first on-orbit use of such a large quantity of series-connected individual pressure vessel (IPV) Ni-H<sub>2</sub> battery cells, in an ORU/Battery (38/76 cells) configuration. Previous

ground testing had been performed on 22 IPV NiH<sub>2</sub> cells in series (Lowery, et al, 1990). Therefore, during the ISS program development stage, it was important to demonstrate that the “as-designed” battery could be successfully run. This was accomplished at the Power Systems Facility (PSF) Laboratory at NASA Glenn (then NASA Lewis) Research Center in Cleveland, Ohio in 1992. Two Engineering Model ORUs in series were subjected to 3,000 LEO peaking cycles at 35% DOD. The test demonstrated that the ORUs exceeded the ISS design requirements for electrical performance, heat generation, thermal uniformity, and charge management (Cohen and Dalton, 1994).

### ORU DESIGN CONSIDERATIONS

Remembering that the original ISS battery design effort began in 1988, a long-life, high-performance battery was needed. Therefore, state-of-the-art Ni-H<sub>2</sub> IPV chemistry was chosen at that time, and designed to meet the following ORU requirements:

- 6.5-year design life
- 81-Amp-hr nameplate capacity to limit the maximum reference DOD to less than 35%
- Contingency orbit capability consisting of one additional orbit at reduced power after a 35% DOD without recharge
- 5-year MTBF
- Easy on-orbit replacement utilizing the robotic arm.

The cells selected for use in the Battery ORUs are manufactured by Eagle Picher Industries. The cells are RNH-81-5 EPI IPV NiH<sub>2</sub>, and utilize a back-to-back plate configuration. They are activated with 31% potassium hydroxide (KOH) electrolyte. The ORUs are assembled and acceptance tested by Space Systems/Loral.

### ISS BATTERY CONFIGURATION

The Battery Subassembly ORU, as designed and built, is pictured below in Figs. 2 and 3.

NiH<sub>2</sub> cells for the current 12 ISS Battery ORUs were manufactured and activated 3.6 to 4.4 years prior the November 30, 2000 launch date. The flight ORUs were used for IEA systems ground testing and final checkout, but were stored open-circuit, discharged, and at -10 °C when they were not in use.

Twelve Battery ORUs were integrated onto the P6 IEA in July 2000 at the Kennedy Space Center (KSC). These 12 ORUs comprise six separate batteries, with three batteries on each of two power channels. For the P6 IEA, these power channels are designated as 2B and 4B. During insolation, power is supplied to the source bus by solar arrays that meet the demands of user loads as well as battery recharging. The batteries interface through a Battery Charge/Discharge Unit (BCDU) and provide the power to the source bus for the ISS during eclipse periods.

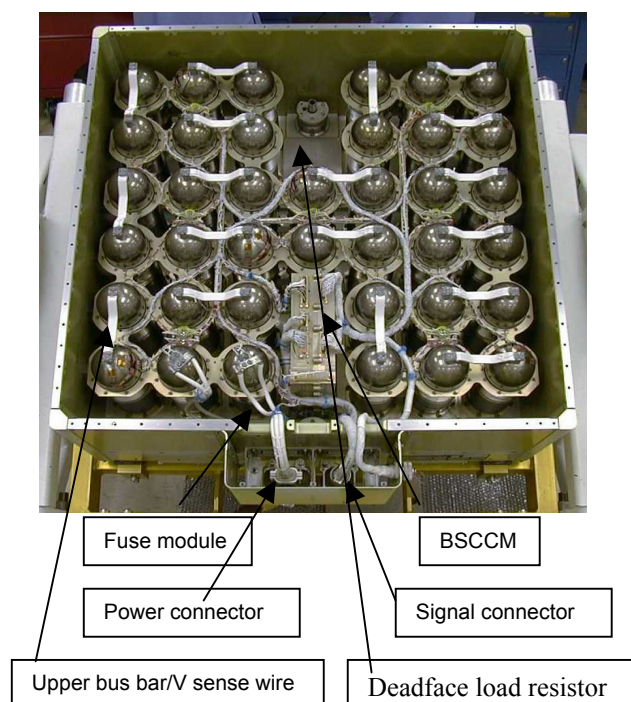
Each ORU is individually fused for fault propagation protection of the EPS in the event of a cell short. The 120-amp fuse block consists of two parallel fuse strings, one 60 ampere string on each power cable. The fuses are constructed using high voltage, high reliability space rated components. Each battery ORU also contains a letdown resistor that connects across the power terminals and provides the capability to individually discharge the hardware at the ORU level.

The battery ORU contains a Battery Signal Conditioning and Control Module (BSCCM). The BSCCM provides conditioned battery monitoring signals from the ORU to the Local Data Interface (LDI) located within the BCDU. Available data includes 38 cell voltages, four pressure (strain gauge) readings, six cell and three baseplate temperatures. This data is provided as an analog multiplexed voltage. A separate signal provides ORU total voltage output. The BSCCM also accepts and executes commands from the BCDU/LDI to control ORU cell heater and resistor letdown functions.



**FIGURE 2. ISS BATTERY SUBASSEMBLY ORU WITH MLI BLANKET**

For battery charging, the BCDU conditions power from the 160 V source bus and charges the battery at pre-determined currents that are calculated based on State of Charge (SOC). The charging algorithm, based on a temperature and pressure SOC calculation, was described in a previous paper (Cohen and Dalton, 2001). During periods of eclipse, the BCDU extracts power from the battery, conditions this power, and supplies power to the source bus.



**FIGURE 3. ISS FLIGHT MODEL BATTERY SUBASSEMBLY ORU WITH COVER REMOVED**

The batteries are actively cooled using the ISS Thermal Control System (TCS). The battery cells are assembled in an ORU box, using a unique finned radiant heat exchanger baseplate. The ORU is then mounted on the IEA using ACME screws and mated to the TCS. The TCS was designed to maintain the Battery ORUs at a nominal operating temperature range of  $5 \pm 5^\circ\text{C}$  ( $41 \pm 9^\circ\text{F}$ ) with minimum heater operation when run at a 35% DOD LEO regime.

### ISS ON-ORBIT OPERATION

The ISS main power system charge algorithm has pre-set parameters. Maximum charge rate is determined and set based on the on-orbit operation need. Currently, a 50-Amp maximum charge rate setpoint is employed due to operating scenarios that feather arrays to save fuel and/or reduce the possibility of charge build-up on the ISS structure during EVA activity. As such, it is necessary to replenish the battery energy used during eclipse as quickly as possible when it is available from the solar arrays. The taper charge profile is pre-programmed in a look-up table with the following parameters:

SOC%	20	85	90	94	96	98	1.00	1.01	>1.05
Chg Rate (Amps)	50	50	50	50	40	27	10	5	1

The above table is on-orbit programmable and can be revised to allow optimal charge rates for

changing operational scenarios, as well as for compensation of changing battery performance characteristics caused by aging.

### ISS ON-ORBIT DATA

The ISS on-orbit data is telemetered to the ground, and is available real time through data screens on consoles located in the Engineering Support Rooms (ESRs) and the Mission Engineering Room (MER). Stored, long-term data can be accessed from the Orbiter Data Reduction Complex (ODRC) through the consoles. The on-orbit start-up procedures and the battery initial performance were reported by Cohen and Dalton, 2001.

Representative, current on-orbit data is shown following the text in Figs 6 through 15. This data is for flight days 117 (April 27, 2002) for channel 2B and 124 (May 4, 2002) for channel 4B. As of these dates, the batteries had completed approximately 8,200 and 8,300 LEO cycles respectively. The data depicts one battery for each channel. Spaces in the data are caused by data drop-out and are not intentional omissions. The data clearly shows that the batteries are performing within their design specifications over the operational range.

For the referenced data:

- Battery voltage (76 cells) 95 to 117 Vdc (Figures 6 and 7)
- Maximum charge rate 50 Amps (note that due to ISS EPS conventions, charging current is shown as negative)
- Cell voltages  $\sim 1.25$  to  $\sim 1.55$  Vdc (Figures 8 and 9)
- Average ORU temperature range  $\sim 0.0$  to  $4.4^\circ\text{C}$  (Note heater cycling due to ISS operation at less than ORU power design loads) (Figures 10 and 11)
- Average battery pressure  $\sim 563$  to  $\sim 720$  psi (note: 4B2 delta pressures between ORUs) (Figures 12 and 13)
- Average SOC  $\sim 80\%$  to  $\sim 104\%$  (Note: Batteries on both channels are operating well below DOD design point, with 4B running at lighter load than 2B) (Figures 14 and 15)

The cycling regime has been fairly benign over the last 18 months, averaging closer to 20% DOD than the designed-for DOD of 35%. Figure 4 is a plot of actual and predicted DODs based on projected power levels. As shown in the plot, actual DODs to date have ranged from a low of 10% to a high of 35%. Power level projections (Gonzalez, 2001) have been used to predict the DOD during the remainder of the P6 batteries on-orbit operation. These predictions range from 16% to 38% DOD, with an average of about 26% DOD. Using the Space Systems Loral performance-based battery design life model, figure 5, and these predicted DODs, the P6 battery life is expected to exceed the 6.5 year life requirement.

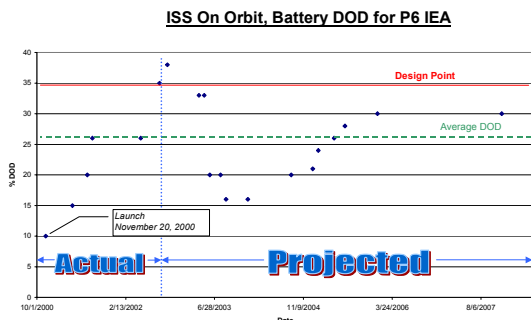


FIGURE 4. DOD FOR P6 BATTERIES

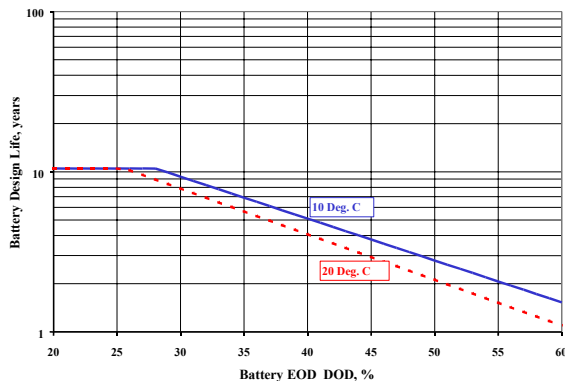


FIGURE 5. BATTERY DESIGN LIFE MODEL

Note in Figure 13 that battery 4B2 has exhibited a pressure divergence between the two ORUs. The divergence has grown with cycling. Battery 4B2 contains a mismatched set of ORUs. In the Battery 4B2, ORU 4B2A has had more ground testing than ORU 4B2B. The ORUs are charged as a pair, but the SOC, and thus the charge rates, are based on the average of the SOC for the two ORUs. This led to an undercharge of 4B2B, and a slight overcharge of 4B2A.

A reinitialization procedure for the battery was performed in February, 2002. The battery was discharged during eclipse, with no charge during insolation periods, until the first cell reached 0.7 V. The individual ORU drain resistors were then engaged. Each ORU was discharged through the resistor until the first cell reached 0.1 V. At the completion of this procedure, the pressure difference had dropped from a high of about 160 psi to 42 psi. The capacity of 4B2B was estimated to be 56 Ah and the capacity of 4B2A was around 76 Ah. The total useable battery capacity will be limited by the 4B2B capacity of 56 Ah, however, at this time it is sufficient to meet ISS requirements.

Additional attempts to equalize the pressures and capacities of these two ORUs will be performed later this year. We have proposed increasing the operating temperature by 2°C and engaging the drain resistor on 4B2A, as well as raising the taper charge current

on both ORUs. A more detailed description of the reinitialization will be reported in a second paper (Hajela and Cohen, 2002).

## CONCLUSIONS

The ISS EPS is successfully maintaining power for all on-board loads. This power is currently supplied by six NiH<sub>2</sub> batteries (three per channel) during eclipse periods. The batteries are designed for a LEO 35% DOD cycle, however, due to the low power demands at this point in the ISS assembly phase, they have been operating between 10 and 35% DOD. The batteries are operating nominally and have exceeded all ISS requirements. The power system will be complete following the scheduled launch of the second, third, and fourth PVMs in April and August of 2002 and January of 2004.

## REFERENCES

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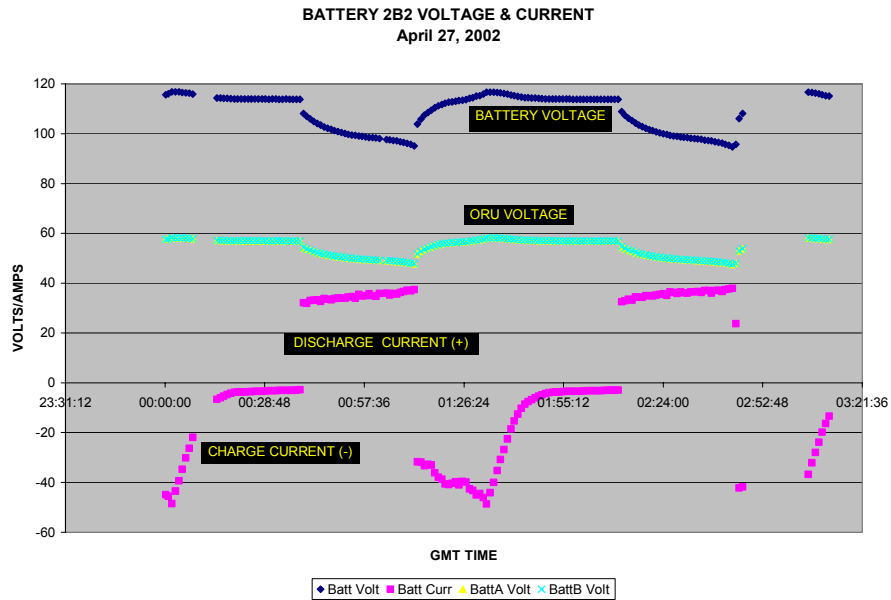
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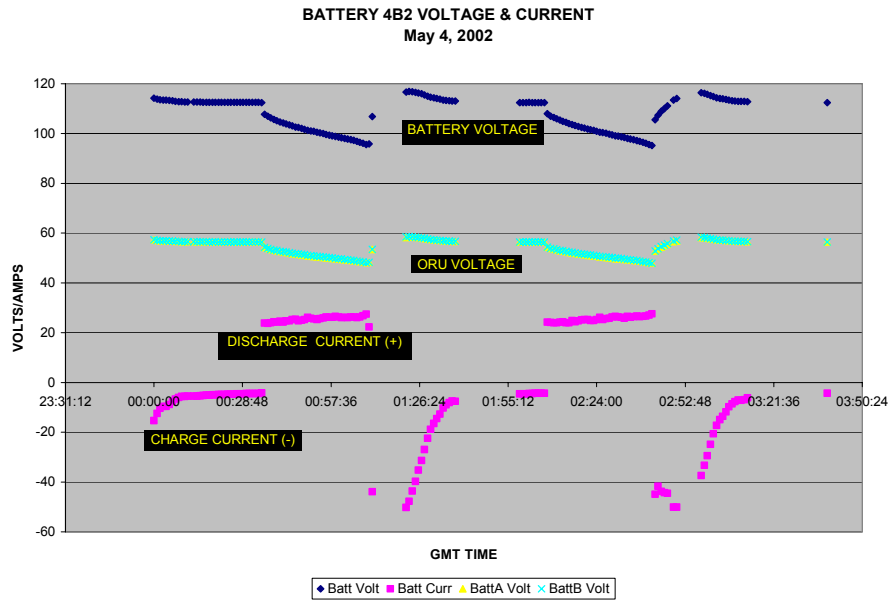
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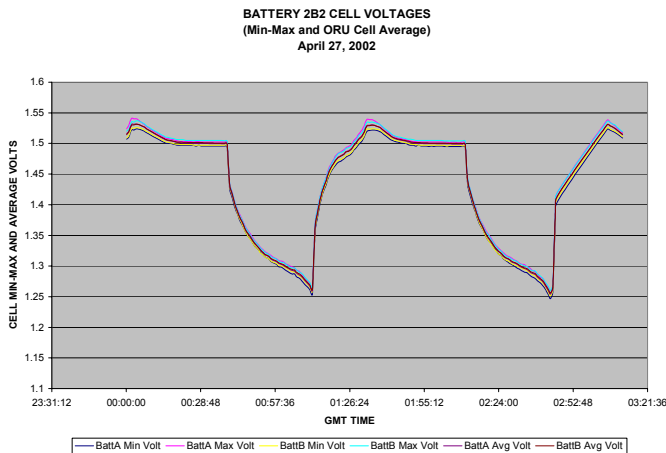




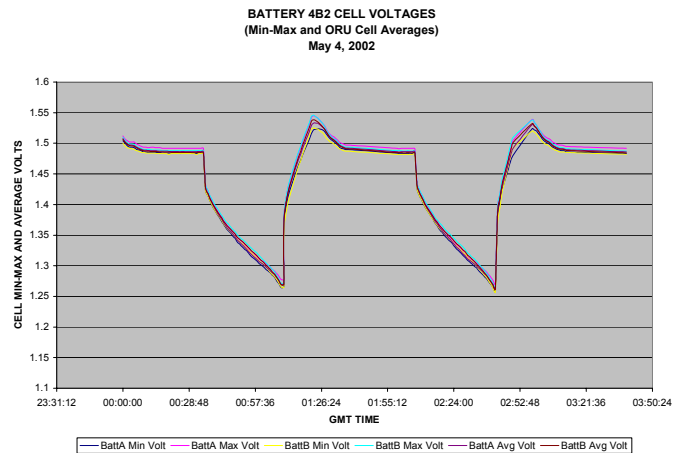
**FIGURE 6. BATTERY 2B2 VOLTAGE AND CURRENT**



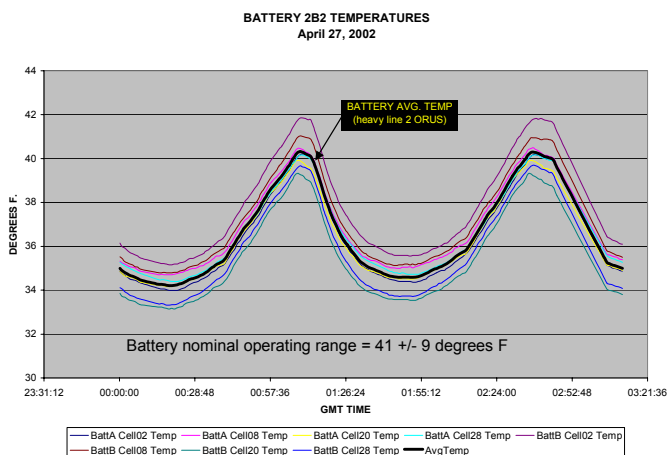
**FIGURE 7. BATTERY 4B2 VOLTAGE AND CURRENT**



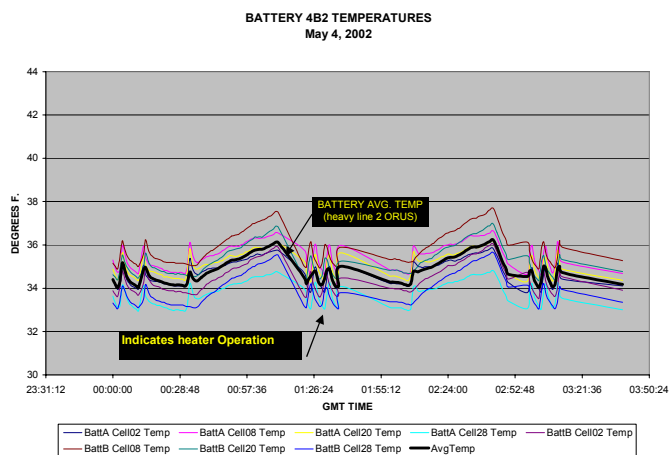
**FIGURE 8. BATTERY 2B2 CELL VOLTAGES**



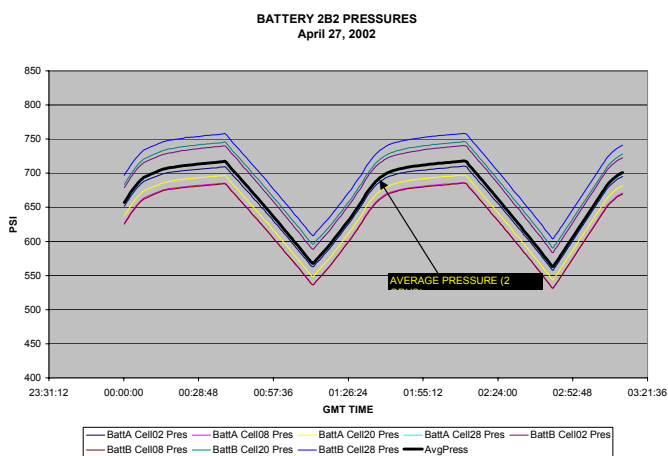
**FIGURE 9. BATTERY 4B2 CELL VOLTAGES**



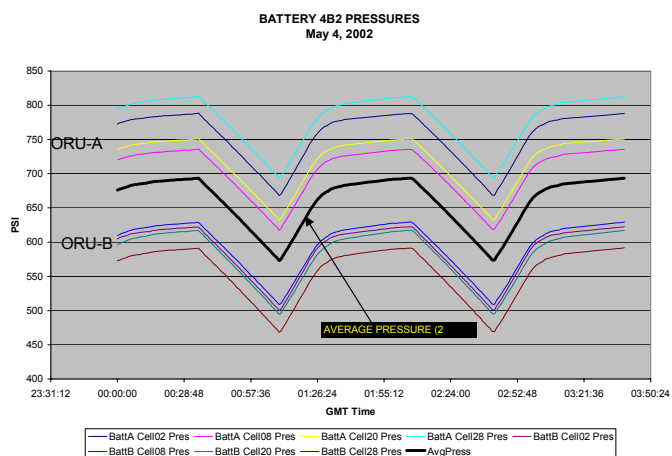
**FIGURE 10. BATTERY 2B2 TEMPERATURES**



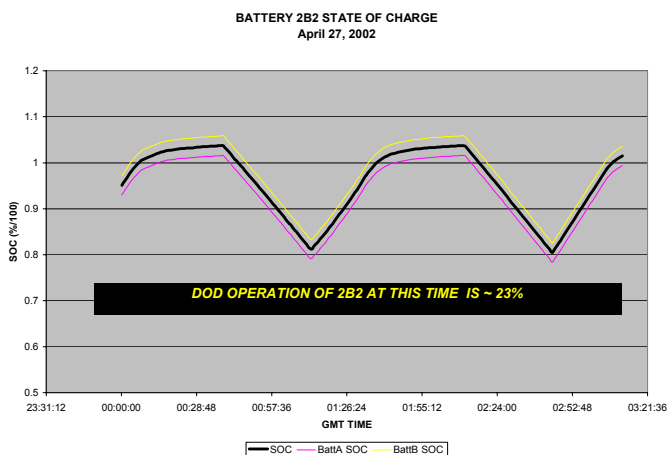
**FIGURE 11. BATTERY 2B2 TEMPERATURES**



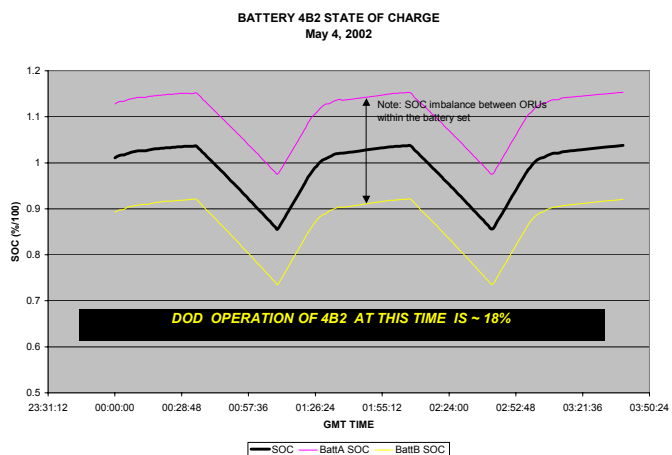
**FIGURE 12. BATTERY 2B2 PRESSURES**



**FIGURE 13. BATTERY 2B2 PRESSURES**



**FIGURE 14. BATTERY 2B2 SOC**



**FIGURE 15. BATTERY 2B2 SOC**